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AUTOMATED FABRICATION TECHNOLOGIES FOR HIGH PERFORMANCE POLYMER COMPOSITES

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SUMMARY: New fabrication technologies are being exploited for building high performance graphite-fiber-reinforced composite structure. Stitched fiber preforms and resin film infusion have been successfully demonstrated for large, composite wing structures. Other automate processes being developed include automated placement of tacky, drapable epoxy towpreg, automated heated head placement of consolidated ribbon/tape, and vacuum-assisted resin transfer molding. These methods have the potential to yield low cost, high performance structures by fabricating composite structures to net shape out-of-autoclave.

KEYWORDS: automation, powders, ribbon, tape, robot, tow placement, resin transfer molding, resin film infusion

1.0 INTRODUCTION

To be economically viable for high performance applications, fiber reinforced polymer composite fabrication must utilize high quality material forms and fully exploit automated processing technology. Selected automated processes employed in the composites industry include the textile processes of weaving and braiding in combination with vacuum assisted resin transfer molding (VARTM) and resin film infusion (RFI) and automated tow/tape placement (ATP).

Stitched preforms combined with VARTM have significant potential for enabling cost effective composite structures. A popular VARTM method is a technique called SCRIMP™ that has gained widespread use for cost-effective fabrication of large thick glass structures such as one-piece boat hulls. In a VARTM method (Ref 1), resin is injected under vacuum directly into a textile preform laid in a mold, namely, a one-sided tool used in conjunction with a flexible bag. The use of preimpregnated fabric or unitape is eliminated thereby eliminating freezer storage of prepreg materials and subsequent shelf life problems. Resin and fiber are used in the lowest cost forms. RFI technology reached its zenith with the development of stitched preforms impregnated with high performance aerospace epoxies such as 3501-6 to make thick wing cover panels which were used to fabricate wing boxes under a contract to The Boeing Company in Huntington Beach, CA (Ref 2). The major elements of this technology will be discussed. Automated cost-effective fabrication of dry stitched preforms will be described in connection with both VARTM and RFI.

The automated placement of composite tow/tape is one of the more promising fabrication methods for rapid, cost effective, net shape composite part manufacture (Ref 3). To apply this technique in various aerospace research programs, NASA Langley Research Center is emphasizing an approach where preconsolidated high temperature, thermoplastic, graphite fiber reinforced ribbon or tape is thermally welded on-the-fly (Ref 4). This approach provides for in-situ consolidation of the part and eliminates the need for laborious debulking and autoclave post-placement processing. Results will be presented for fabrication of preconsolidated composite ribbon and tape and automated fiber placement.

2.0 STITCHED PREFORMS AND RESIN TRANSFER MOLDING

2.1 Fabrication of Textile Preforms

High quality fiber preforms are required to produce high quality composite parts using resin transfer molding (RTM) processes. Various types of textile material forms have been used to fabricate near net shape preforms for resin transfer molding of composite aircraft structures (Fig 1). Multiaxial warp knitting is a highly tailorable automated process that produces multidirectional broadgoods for large area coverage. Two-dimensional and three-dimensional braids are used to create stiffeners, frames and beams with complex cross-sections. Through-the-thickness stitching is an effective way to debulk preforms and to achieve improved out-of-plane strength and damage tolerance of composite structures.

Major advancements have been made in through-the-thickness stitching technology during the past 25 years (Fig 2). Early stitching studies by NASA and McDonnell Douglas (now Boeing) used a limited capacity, extended arm, single needle machine to produce preforms for damage tolerance testing. The next generation stitching machine was computer controlled and utilized quilting technology. This machine was limited in size and stitching speed so NASA and McDonnell Douglas entered into a contractual agreement with Ingersoll Milling Machine Company and Pathe Technologies, Inc., to develop a high speed, multiple head stitching machine capable of stitching large wing skins for commercial aircraft. This second generation machine is shown in Figure 3 and has four stitching heads that can stitch a preform 3.0m by 15.2m by 38.1mm at 800 stitches per minute. The stringer stiffened preform shown on the advanced stitching machine was used to produce a wing cover panel for the NASA Advanced Subsonic Technology Composite Wing Program.

2.2 Vacuum Assisted Resin Transfer Molding (VARTM)

VARTM processes have been used for many years to fabricate fiberglass reinforced composite structures. The U.S. Naval Surface Warfare Center in Bethesda, MD has been the major promoter of this technology for composite marine applications (Ref 5). The major advantages of VARTM processes compared to conventional autoclave processes are the lower cost of tooling, reduced cost of energy to cure composite parts, and almost unlimited part size (i.e., no size constraints based on the size of the autoclave). Until recently, VARTM was primarily used to fabricate glass reinforced polyester and vinyl ester composites. However, due to recent developments in resin and preform technologies, aircraft manufacturers are beginning to show significant interest in VARTM processes for graphite-epoxy and graphite-bismaleimide composite systems. One drawback to VARTM processes has been its low fiber volume fraction compared to the higher fiber volume fractions achievable with autoclave processes. However, stitching and debulking methods have been developed to achieve preforms that are near net shape with little or no further compaction required during processing.

NASA has conducted contractual research with Seemann Composites, Inc. to establish the feasibility of another VARTM process to produce aircraft quality composite structures. A proprietary process, called SCRIMP™ (Seemann Composites Resin Injection Molding Process) utilizes a resin distribution media to achieve full wet-out of the preform (Fig 4). In addition, Seemann has developed a reusable bagging concept that eliminates most of the costs associated with conventional bagging procedures. Seemann Composites has also demonstrated SCRIMP™ for lightly-loaded general aviation aircraft structures. A concept using one-sided tooling and a graphite preform for a small aircraft fuselage section has been demonstrated (Fig 5a, 5b). Current and future tooling developments for integral heating will eliminate the need for oven cure and postcure of composite parts fabricated with VARTM processes.

NASA is also investigating the feasibility of SCRIMP™ to produce aircraft quality heavily-loaded primary structures. Additional technology development is required to achieve dimensional control and acceptable fiber volume fractions for thick structural elements. Innovative tooling concepts will be required to meet typical assembly tolerances for aircraft structures. Stitching will be required to achieve near net shape for the preform prior to resin injection. The reusable bagging concept for a three stringer panel representative of wing structure is shown in Fig 6. The ease of removing this bag from the stiffened panel is illustrated in Fig 7, and the finished panel (after resin injection and cure) is shown in Fig 8.

2.3 Resin Film Infusion (RFI)

RFI is another process being pursed by NASA and The Boeing Company to develop cost-effective wing structures for commercial transport aircraft. The RFI process developed by Boeing(formerly McDonnell Douglas) consists of an outer mold line tool, an epoxy resin film, a near net shape textile preform, an inner mold line tool, and a reusable vacuum bag. Thick film plates of resin (called "resin slabs") are placed on the outer mold line tool, and the preform and inner mold line tools are placed on top of the resin. The entire assembly is covered with a reusable vacuum bag, and the part is placed inside an autoclave. After the resin is melted, vacuum pressure is used to infuse resin into the preform. Once infiltrated, the part is cured under pressure and temperature in the autoclave. The keys to producing aircraft quality parts with the RFI process are understanding the compaction and permeability characteristics of the preform and understanding kinetics and viscosity profiles for the resin as a function of temperature.

The stiffening elements and tooling blocks must be precisely located to achieve the required dimensional tolerances. The advanced stitching machine discussed previously (Fig 3) was used to locate structural details such as ply drops, stiffeners, interleaved spar caps, and rib clips. Fig 9 shows a vacuum bagged wing panel prior to infusion and cure. Fig 10 shows the completed composite panel after cure. It should be noted that the cured composite wing panel has no mechanical fasteners since all the stiffening elements are stitched to the skin.

To eliminate trial and error process development, analytical models are required to predict resin flow into textile preforms. The models must be verified through precise experiments to demonstrate the modeling accuracy. Three-dimensional models are required to capture response adequately for complex preforms such as wing cover panels that contain stitched/knitted fabric skins and stitched/braided stiffeners. The objectives of the analytical model are to predict the resin flow front position, resin viscosity, and degree of resin cure as a function of temperature and time. A 3-D RFI process simulation model is under development by Virginia Polytechnic Institute and State University (Ref 5). The RFI simulation includes resin flow, heat transfer, and thermochemical elements. A schematic of the 3-D finite element model for infusion of a stitched blade stiffener is shown in Fig 11. Experiments are currently being conducted to verify accuracy of the 3-D finite element model. For a two-stringer stitched panel, the predicted temperature distribution was within 6 percent of measured temperature and the predicted resin wet-out times were within 4 to 12 percent of measured times.

3.0 AUTOMATED TOW/TAPE PLACEMENT

Materials and processing evaluation activities carried out with a prototype machine at Langley were an integral part of several NASA aerospace research programs involving even larger and more sophisticated proprietary machines being developed at several corporate research laboratories. These NASA/industry research programs are addressing ATP material form development as well as ATP requirements such as precise control of robot head positioning, material placement rates, heat delivery to the lay-down zone and cut/add, start/stop capability.

3.1 Preconsolidated Composite Ribbon and Tape

Automated tow/tape placement (ATP) requires high quality, fully consolidated, thermoplastic ribbon and tape with precise dimensional tolerances. NASA has developed ways to fabricate the required product forms subject to the following restrictions: (a) utilize no solvents that would have to be removed in subsequent fabrication steps; and (b) avoid melt impregnation since high performance, high molecular weight thermoplastics such as polyimides and polyarylene ethers have high melt viscosities. Melt viscosities for candidate resins were lowered by judicious alteration of the molecular weight and main chain manipulation, even to the point where RTM and RFI processes were enabled with some of the resins. The scheme finally developed at Langley utilized impregnation of finely ground polymer powder particles onto a spread, unsized carbon fiber tow bundle followed by thermoplastic forming of the powder-coated tow (called a towpreg) into consolidated ribbon and tape.

Processes for making towpreg have been developed from both slurry and dry powder techniques (Ref 6). An optimized process, called the "powder curtain" was found to be the most efficient way of distributing the polymer particles throughout continuous filament tows (Fig 12). The resulting towpreg yarn was flexible, bulky, and abrasive. Composite laminates were made with this material by frame-winding followed by press molding. These laminates had mechanical properties (Table 1) that compared quite favorably to properties from laminates made from solution prepregging followed by devolatilization and press molding (Ref 7).

Heated, robotic placement heads are generally designed to utilize stiff, preconsolidated ribbons or tapes having consistent cross-section, properties very different from the towpreg described above. A number of debulking techniques were studied to convert powder-coated towpreg yarns into stiff, fully preconsolidated ribbon and tape (Ref 8). Issues included towpreg material quality, transverse squeeze-flow, appropriate timing for heating and pressure application, and tool contact/release. Several processing methods were designed, built and experimentally evaluated. Four powder-coated towpreg yarns, Aurum™-500/IM-8, PIXA-M™/IM-7, LARC™-IA/IM-7 and APC-2™ (PEEK/AS-4) were used in this evaluation. Reactive plasticizers and solvents were excluded. The work concentrated on the fabrication of 0.63 cm wide ribbon from two 12K IM-7 powder coated tows and 7.6 cm wide tape from 25 powder-coated tows (Ref 8, 9).

A novel processing technique was developed for fabricating the consolidated ribbon/tape. The processing equipment was comprised of two primary components (Fig 13). The ceramic hot bar fixture facilitated transverse melt squeeze flow while the cool nip-roller assembly solidified the ribbon/tape into preconsolidated ribbon/tape with consistent cross-section. The heat transfer and pulling force were modeled from fundamental principles to develop a basic understanding of the process for application to a variety of polymer materials.

3.2 Automated Fiber Placement

Fiber placement differs from filament winding in that it requires the tow placement tool tip to contact the surface of the part rather than floating off the part. This allows for placement in non-geodesic paths which may be required for complex parts (Ref 3). Contrasted to filament winding, which is limited to continuous placement on closed part geometry, ATP with its cut/add capability can place on open as well as closed parts.

Specific work cell configurations for fiber placement depend upon the geometry of the parts to be fabricated. However, the following elements are common to all fiber placement machines:

- Placement Head
- Automated Machine Platform
- Electronic Controls and Software
- Placement Tool

During automated placement, preconsolidated composite ribbon or tape is fed from spools through a delivery system located on the placement head. A band of collimated ribbons or a tape is placed with heat and pressure to laminate it onto the work surface.

The placement head is a stand-alone end effector that feeds, cuts, places, and laminates the ribbons or tape (Ref 10). The placement head is supported by an automated machine platform. This platform is usually a commercially available gantry or an articulated arm unit to which additional degrees of freedom may be added (Ref 3).

A prototype automated thermoplastic fiber placement machine for materials and processing evaluation has been developed by NASA (Ref 11). The machine, shown in Fig 14, was manufactured by Automated Dynamics Corporation (ADC) and is comprised of an Asea Brown Boveri robotic arm with an ADC thermoplastic fiber delivery head (Fig 15) and placement tools. The latter are comprised of both flat and cylindrical steel tooling. The computer control system and software for the work cell were jointly developed by ADC and Composite Machine Company (CMC). ADC performed the total system integration.

Machine development for thermoplastics has dealt with the use of hot gases, lasers, focused infrared radiation (IR) and combinations of these heat sources. The most effective heat source was a hybrid focused infrared-hot gas tandem. A reflector and compact IR lamp was placed as close to the nip point as possible to deliver, concomitantly with the heated nitrogen gas torch, the highest heat flux to the nip region (Ref 12). This arrangement allowed the compaction roller to operate at much lower temperatures than normally used which, in turn, reduced sticking of resin and fiber onto the roller. Unidirectional panels placed under conditions of optimum strength had an average crack initiation toughness comparable to those of autoclave processed panels; without the additional heat source, unacceptable interfacial strengths would have resulted at lower roller temperatures. Current work also is directed toward start-on-the part, turning radius limitations, autoadhesion requirements, and development of sensors that give on-line part quality information. The latter would yield a remarkable cost-savings for fabrication of commercial aerospace composite structure when used to repair defects during on-line placement.

Analytical consolidation models have been developed to relate ATP machine design, operating parameters, and sensor readings to the processing conditions necessary for making quality composite parts. In-situ bonding models have served to establish a processing window bounded by the upper and lower limiting values of the processing conditions within which acceptable parts can be made. The models attempt to describe the mechanisms involved in the ATP process. These include heat transfer, tow thermal deformation and degradation, intimate contact, bonding and void consolidation (Ref 13). Finite element analysis, neural networks and fuzzy logic techniques have been used in these computer-based models (Ref 14). Most recently, a new start-on-the-part transient model for in-situ ATP of thermoplastics has been developed (Ref 15).

One of the primary purposes for developing models has been to aid on-line control. The computer execution time is therefore critical. Currently, even in their most simplified form, most models take too long for predictive use on-line. As a result, the models are run off-line for various parameters in the processing window and a computer look-up table is constructed that can be used as a guide to on-line control (Ref 14).

During the past year, in-situ consolidated laminates have been prepared from high temperature polyimides such as AURUM™ PIXA/IM7, AURUM™ PIXA-M/IM7 and LARC™ PETI-5/IM7 and polyarylene ethers and sulfides such as APC-2™ (PEEK)/AS4), APC-2™ (PEEK)/IM6, PEKK/AS4 and PPS/AS4. The thermosetting materials such as the LARC™ PETI-5/IM7 require a high temperature postcure to optimize their performance. Some properties of PEEK and PIXA panels made by ATP on large industrial equipment are given in Table 2 and compared with properties obtained from panels made by hand lay-up/autoclave procedures. The ATP panels exhibited from 85 to 93 percent of the properties of composites made by hand lay-up/autoclave. These results indicate that heated head ATP technology can be used to effectively fabricate quality, high performance composite laminates. The goal for ATP structures is to achieve parity with the mechanical properties from structures processed using hand lay-up/autoclave techniques.

4.0 CONCLUDING REMARKS

Major advancements have occurred in the automated fabrication of composites containing textile preforms. Automated processes that produce multidirectional broadgoods for multiaxial knitting coupled with a second generation stitching machine with 4 heads have pushed the resin infusion and resin transfer molding technologies to a high level of accomplishment. Wing cover panels have been successfully fabricated from integrally woven preforms utilizing an outer mold line tool, epoxy resin film, near net shape textile preforms, an inner mold line tool and a reusable vacuum bag via resin film infusion. Low cost vacuum assisted resin transfer molding (VARTM) processes are now being applied to the fabrication of aircraft quality, heavily-loaded primary structure.

Significant progress has been made in developing automated heated head tow/tape placement technology for the fabrication of high performance composite structures. The key activities included development of methods for making quality thermoplastic ribbons and tape, determination of machine design and operating requirements for in-situ placement, and establishment of a base knowledge of the fundamental mechanisms involved in both ribbon/tape preparation and in-situ consolidation.

ATP studies during the period ahead will include the validation of focused infrared/hot gas heating and development of on-line sensors and start-on-the part methods. Particularly important will be material qualification studies at NASA and the fabrication of large test specimens and component structures at several industrial laboratories. VARTM processes need further development to show that aerospace quality parts can be fabricated that have the desired hot/wet mechanical performance. Resin transfer molding modeling studies will focus on the prediction of resin flow into complex textile preforms to insure high quality, high speed fabrication at lower costs.

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Table 1. Mechanical properties of LARC™ IAX/IM7 polyimide composites made by solution and powder-coated prepreg*

Property	Test Temp., °C	Solution Coated	Powder Coated
SBS Str., ksi	RT	15.8	22.1
	177	7.9	8.9
0°Flex. Str., ksi	RT	213	314
	177	105	213
0°Flex Mod., msi	RT	18.6	19.8
	177	15.1	19.8
0°Compress. Str., ksi	RT	167	202
0°Compress. Mod., msi	RT	23.4	23.7

*Data normalized to 60/40 fiber/resin vol. %; Polyimides were formulated to 4% offset in favor of the diamine and endcapped with phthalic anhydride.

Table 2. Open Hole Compression Strengths of Quasi-isotropic Thermoplastic Composites

Process	APC-2™ (PEEK)/AS4	APC-2™ (PEEK)/IM6	AURUM™ PIXA/IM7
Hand Lay-up/Autoclave	47 ksi	46 ksi	46 ksi
Adv. Tow Placement	40 ksi	43 ksi	39 ksi
% Retention	85	93	85

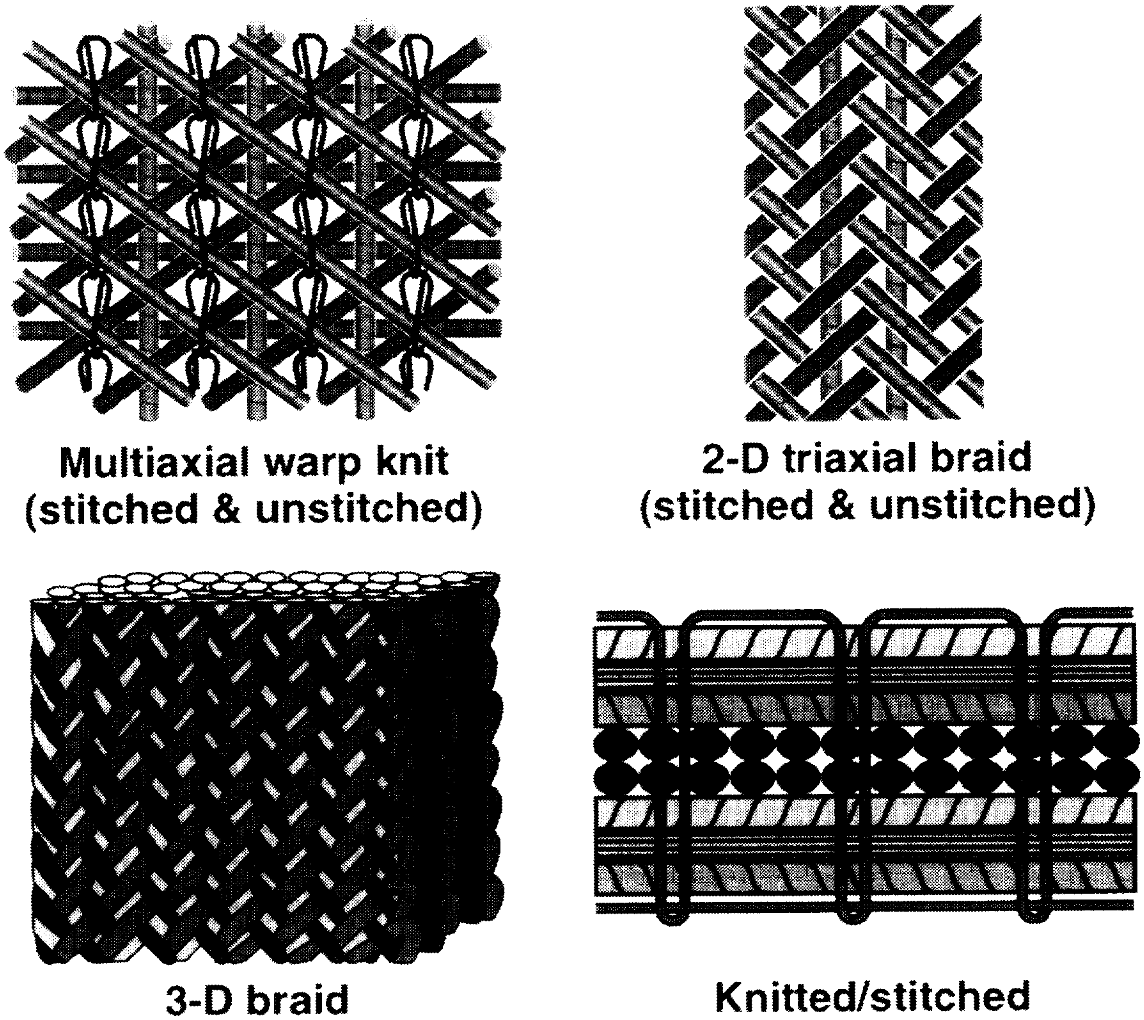


Figure 1. Textile material forms.

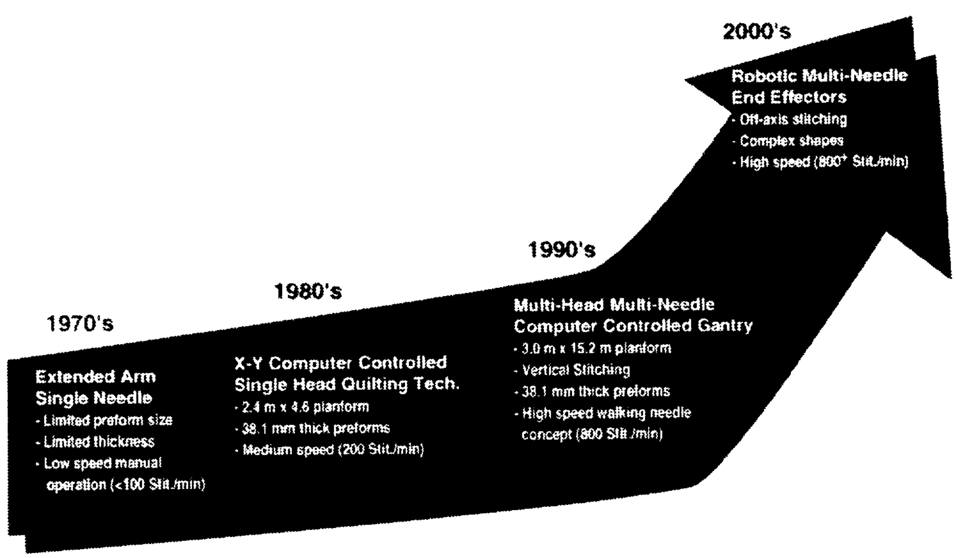


Figure 2. Evolution of stitching technology.

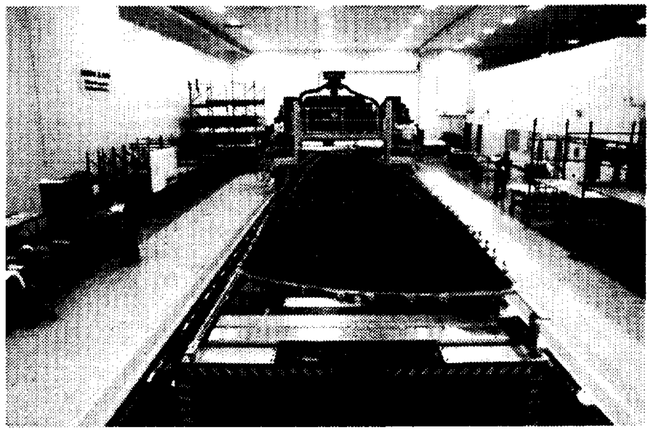
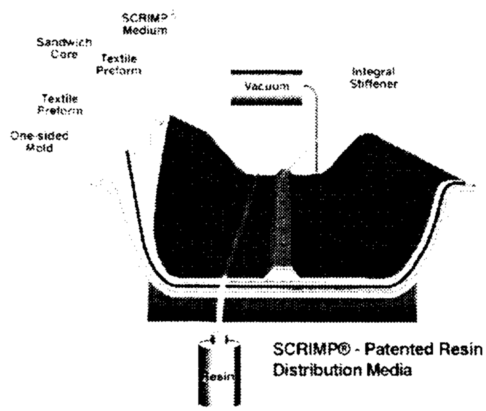
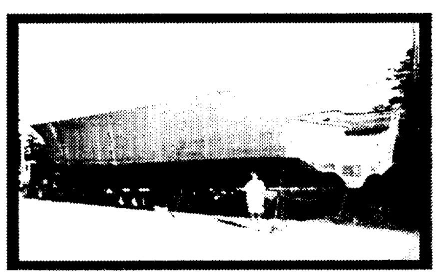


Figure 3. Stitched semi-span wing lower cover preform.



Advantages of low-cost RTM process:
- Resin and fiber used in lowest cost form
- Prepreg process eliminated
- Freezer storage & shelf life problems eliminated
- Low-cost, one-sided tooling
- Low energy, low pressure out-of-autoclave processing
- Utilizes net-shape, damage tolerant textile preforms
- Large integral structure minimizes secondary bonding and fastening

Challenges for aircraft applications:
- *Out-of-autoclave cure resins with adequate properties*
- *Dimensional tolerances with low-cost tooling*



90 ft. one-piece boat hull fabricated with SCRIMP® process

Figure 4. Low-cost vacuum assisted resin transfer molding process.

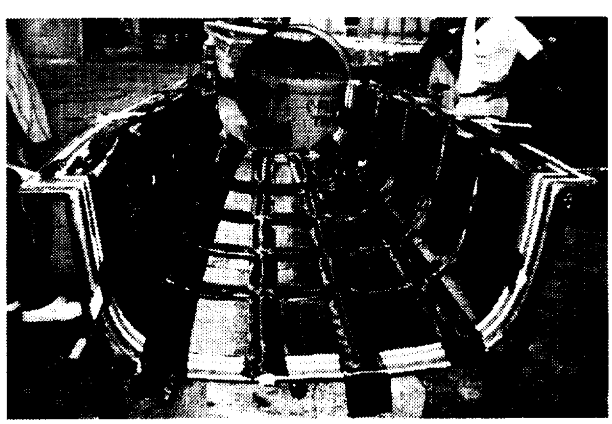


Figure 5a. Vacuum assisted resin transfer molding tooling for fuselage section.

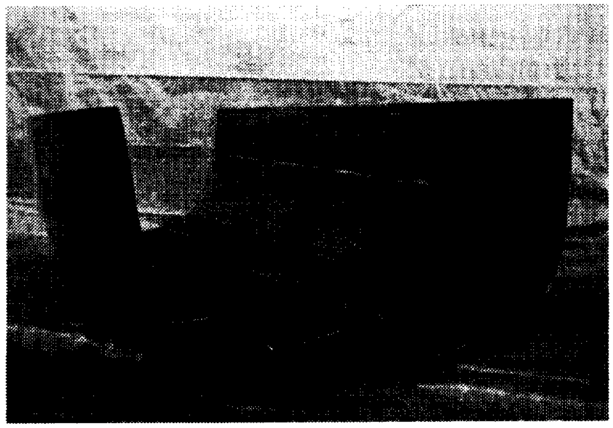


Figure 5b. Completed fuselage section.

Figure 6. Reusable vacuum bag for VARTM of stiffened panel.

Figure 7. Removal of reusable vacuum bag from VARTM stiffened panel.

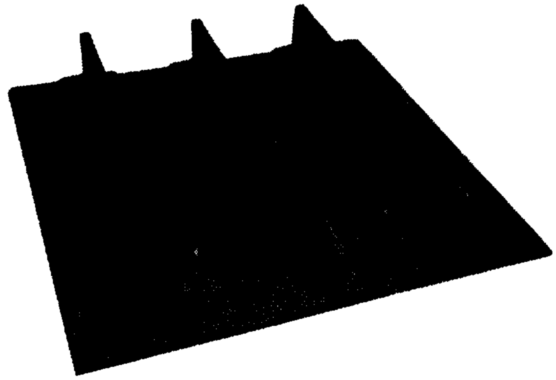


Figure 8. Stiffened panel fabricated by VARTM.

Figure 9. Vacuum bagged semi-span wing tool proof article prior to cure.

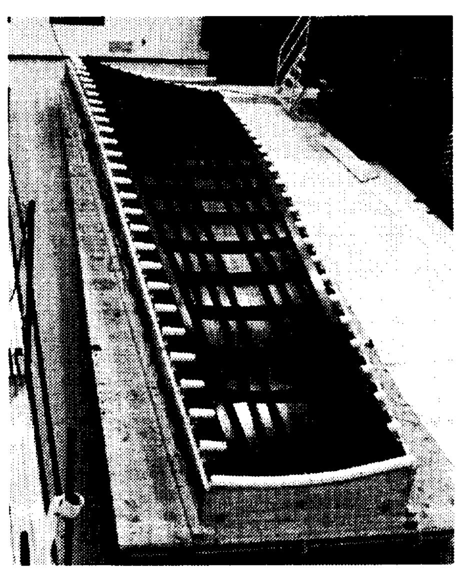


Figure 10. Semi-span wing tool proof article after cure.

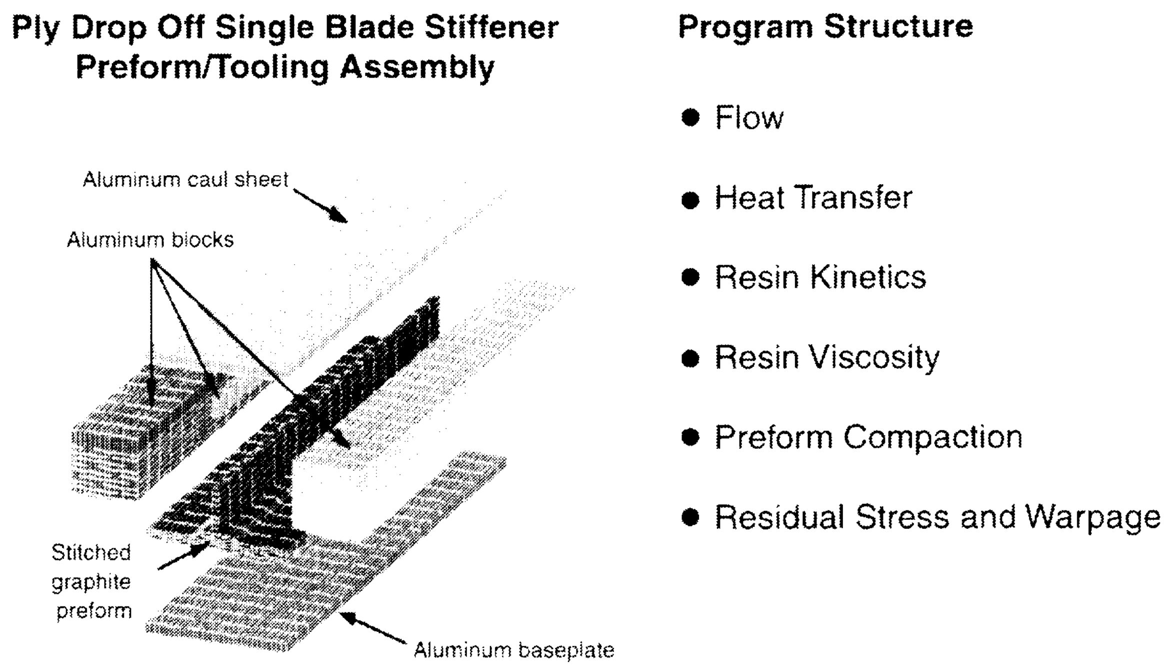


Figure 11. Three-dimensional resin film infusion model.

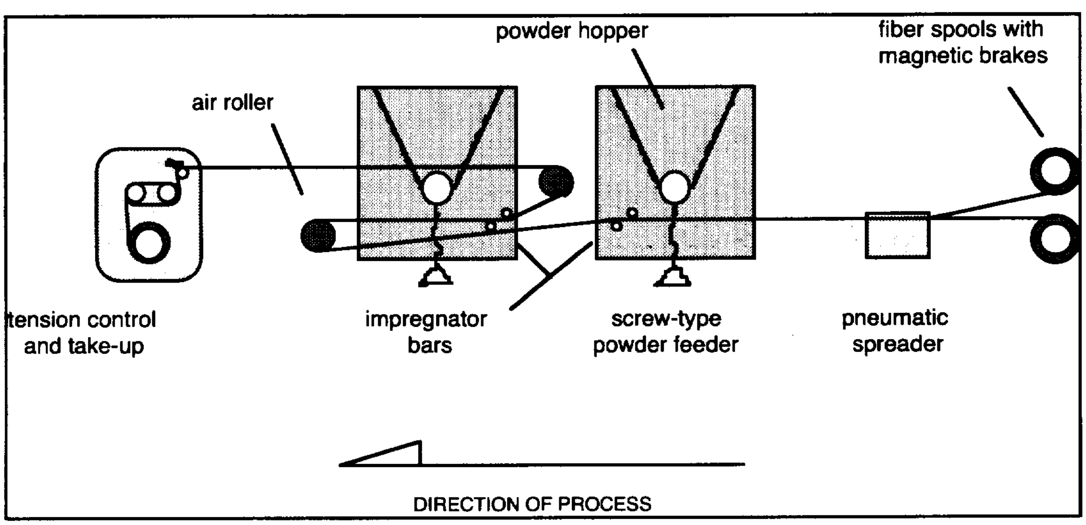


Figure 12. Schematic of the NASA Powder-Coating Line.

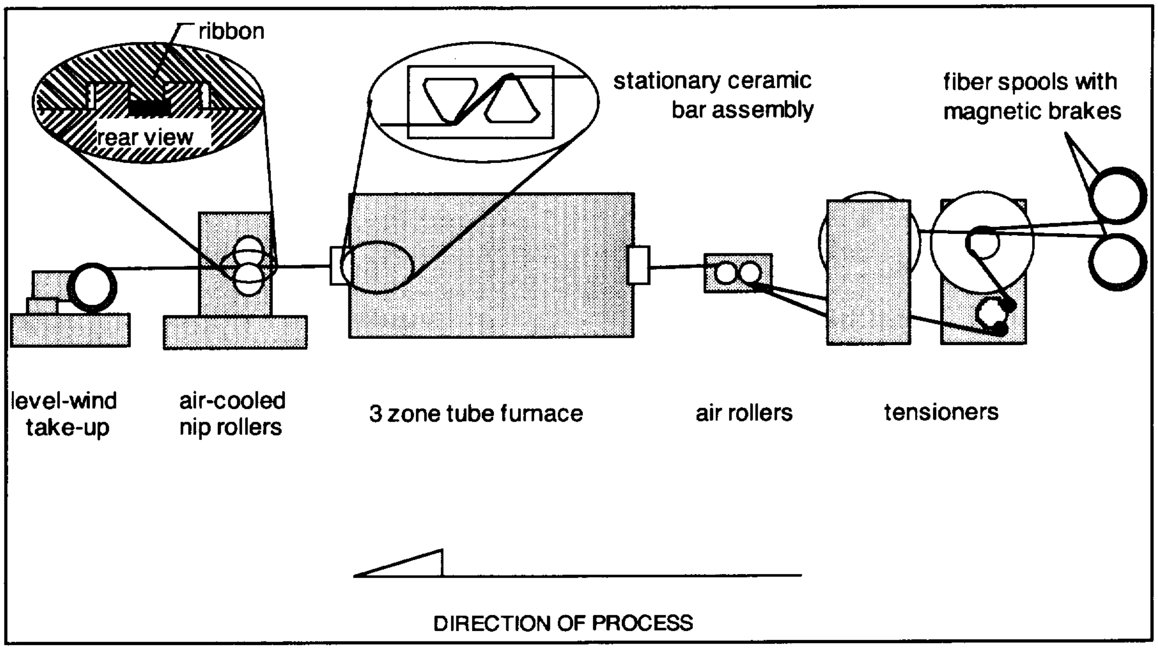


Figure 13: Schematic of NASA Ribbon/Tape Line.

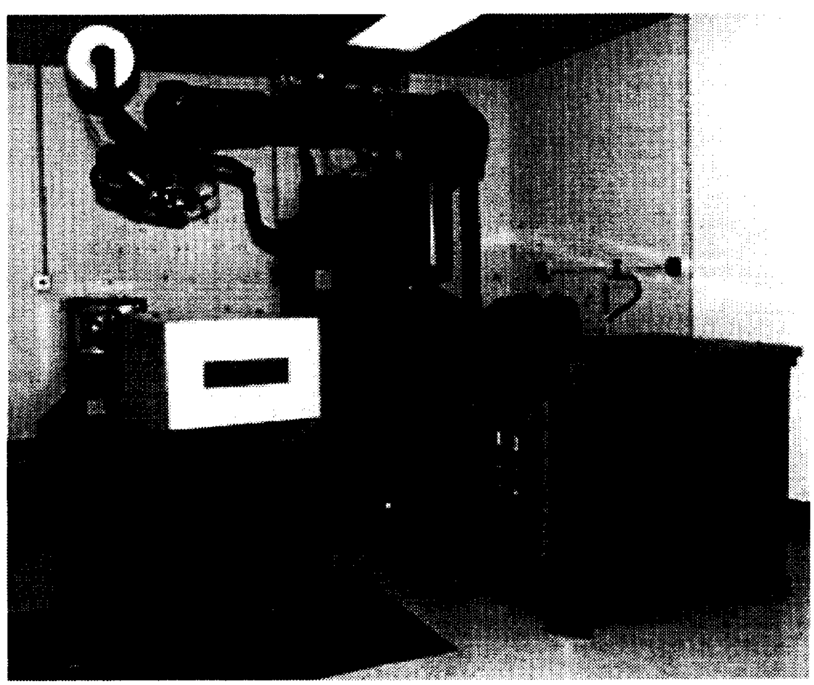


Figure 14. Photograph of NASA Robot, Heated Head and Heated Flat Tool.

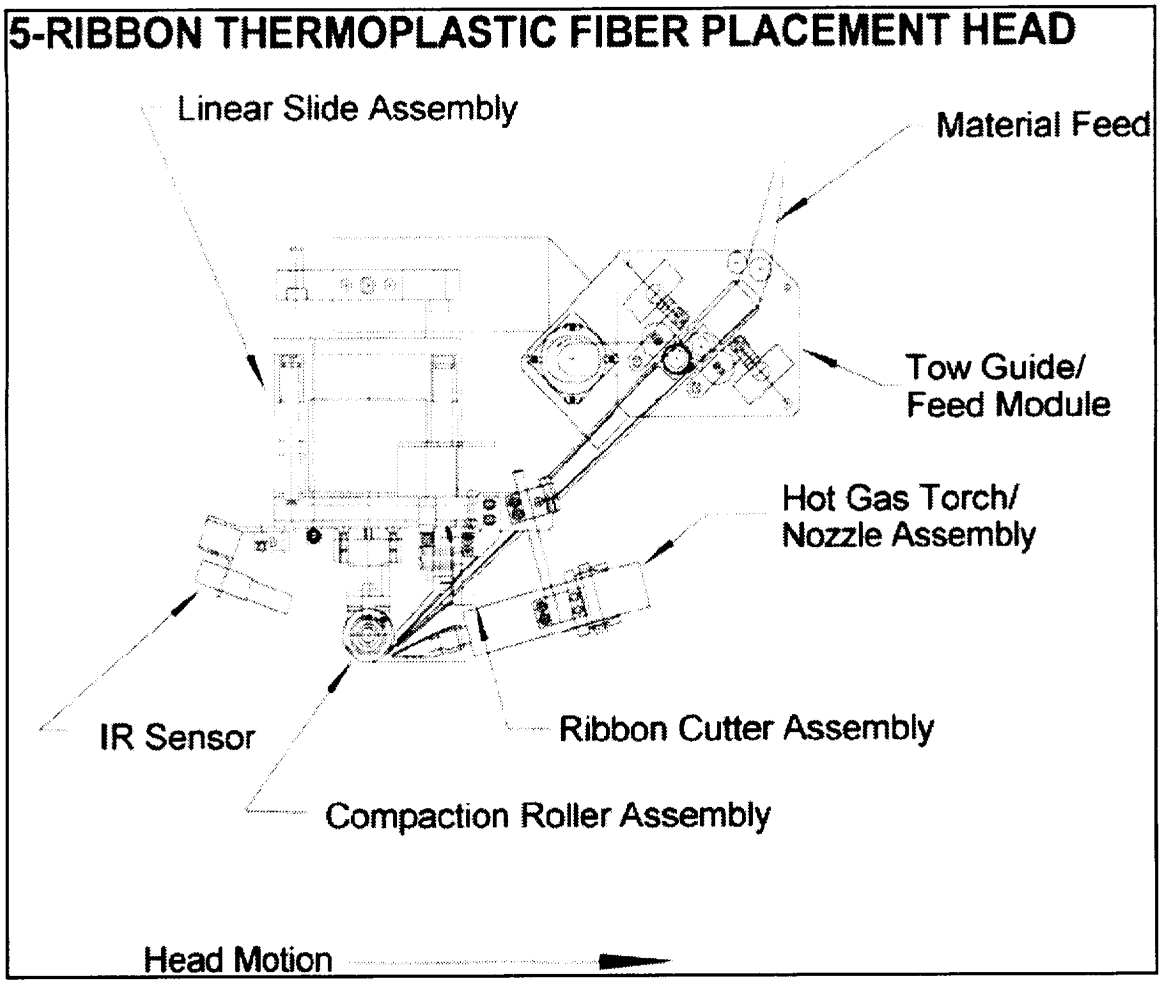


Figure 15. Schematic of the NASA Heated Head.